Short Baseline Physics Working Group

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- LBNE-Physics: [Θ_{13}, δ_{CP}, Mass-Hierarchy]
  ν(Bar)e-Appearance & $\nu\mu$(Bar)-Appearance;

- Precision Measurements: Weak-Mixing Angle, ΔS, Sum-Rules, ...

- Searches

REQUIREMENTS FOR LBL STUDIES

- ✦ *Determination of the relative abundance and of the energy spectrum of the four neutrino species in LBNE beam:* $\boxed{\nu_\mu}$, $\boxed{\bar{\nu}_\mu}$, $\boxed{\nu_e}$, *and* $\boxed{\bar{\nu}_e}$ *CC-interactions.*
  - μ^+/μ^- *separation* $\Longrightarrow$ *magnetized detector;*
  - e^+/e^- *separation;*
  - *Identify* μ^+/μ^- *from* π *and* K *decays in NC interactions or high* $y_{\rm Bj}$ *CC events;* ➾ ν(Bar)μ-Disappearance
  - *Identify* e^+/e^- *from* π^0/γ *conversion near the interaction vertex in NC or high* $y_{\rm Bj}$ *CC events.*
    ➾ ν(Bar)e-Appearance
- ✦ Because Flux(ν_i) ≠ Flux(ν_j) at ND and FD $\Rightarrow$ need σ(CC) & σ(NC/CC)

- ✦ *Measure exclusive and semi-exclusive NC and CC cross-sections: Quasi-elastic, single* π*, Deep Inelastic Scattering (DIS), and coherent.*

- ✦ *Calibration of the absolute neutrino energy scale*

- ✦ *Provide an 'Event-Generator Measurement' for the FD by measuring the detailed topologies (complete hadronic multiplicity) of NC and CC interactions.*

Configurations

ॐ `Standard' LBNE beam

ॐ Option-A: 3+3 years with 700KW ➢ 7.3*10**20 PoT/Yr ⇒ Used for sensitivity

100k ν_μ-CC Events/Pr/ton/10**20 Pr

ॐ ND Configurations: (ND Group: Mauger & Louis)

LAr:

(a)70 tons with no magnetic field

(b)20 tons with magnetic field

Fine-Grain Tracker:

(a)Low Density (0.1gm/cm^3) Straw-Tube Tracker in a B=0.4T with TR, Hermitic ECAL, Muon-detectors

(b)Scintillator Tracker with a downstream muon Spectrometer

H20 Target embedded within a Fine-Grain Tracker:

(a)ν-H2O Interactions: ~1.2tons of H2O

(b)With an additional D2O target, measure an absolute flux measurement using QE(Q**2~0)

ॐ Option-B: Intensity expected with the Proton-Injector

TOPICS AND TALKS

- In-situ measurement of fluxes and backgrounds (docdb#785);
- Requirements for flux determination (docdb#946);
- MINERvA measurements (docdb#894);
- NOMAD measurements (docdb#930);
- Complementarity with JLab measurements (docdb#894);
- Electroweak measurements (docdb#785);
- NC elastic scattering off proton (docdb #774 and 883);
- Strange form factors (docdb#774);
- Nuclear effects in QE interactions (docdb#774);
- Search for high Δm^2 oscillations (docdb#914 and 946);
- Extraction of the fluxes with high Δm^2 oscillations (docdb#946);
- Search for sterile neutrinos (docdb #775 and);
- MiniBooNE low energy anomaly (docdb#775);
- Neutrino magnetic moment (docdb#956);

- Neutrino-induced Proton-Decay backgrounds
- Measurement of Adler sum-rule

IN-SITU FLUX MEASUREMENT

✦ Determination of the absolute flux normalization with 3 independent methods:

- Inverse Muon Decay: $\nu_\mu e^- \longrightarrow \mu^- \nu_e$
- NC elastic scattering off electrons: $\nu e^- \longrightarrow \nu e^-$
- Quasi-elastic scattering on D for $Q^2 \longrightarrow 0 : \nu_\mu n \longrightarrow \mu^- p$

✦ Determination of relative flux as a function of energy with 3 independent methods:

- Low-ν_0 method;
- NC elastic scattering off electrons;
- Quasi-elastic scattering on D for $Q^2 \longrightarrow 0$

ABSOLUTE FLUX DETERMINATION

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ॐ ν-Electron NC Events:

✺ Using Collider measurements, the Weak Mixing Angle (WMA), 0.238 at Q~0.07 GeV, known to ≤1% precision

✺ Identify ν-El elastic NC events

Two Steps to Analysis

✺ Electron-ID: TR

✺ Kinematic cut: $\zeta = P_e(1-\cos\Theta_e) \leq$ Cut

✺ Estimate background and Efficiency

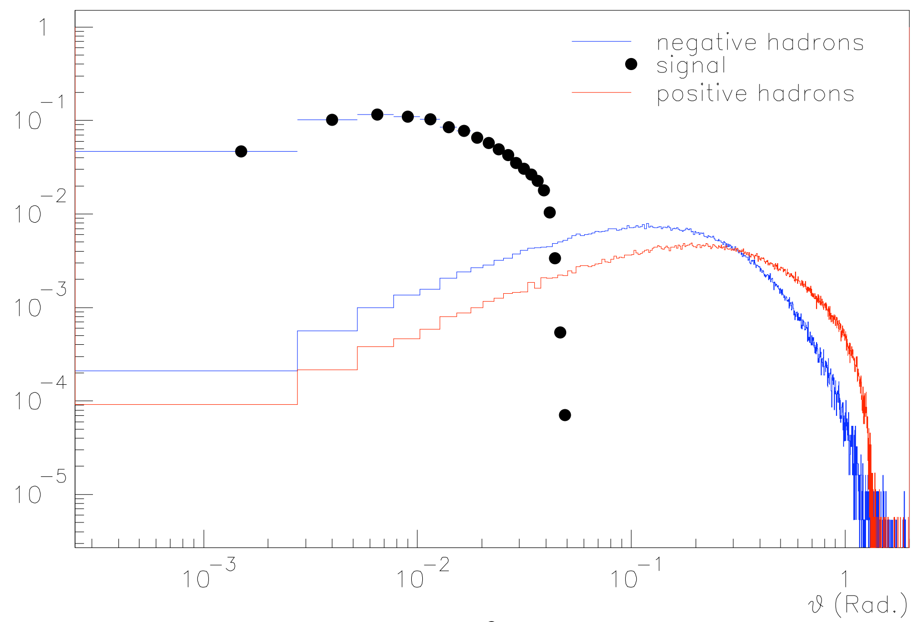
✺ Use the SM-σ(ν-El elastic NC) to obtain the

Absolute ν-Flux

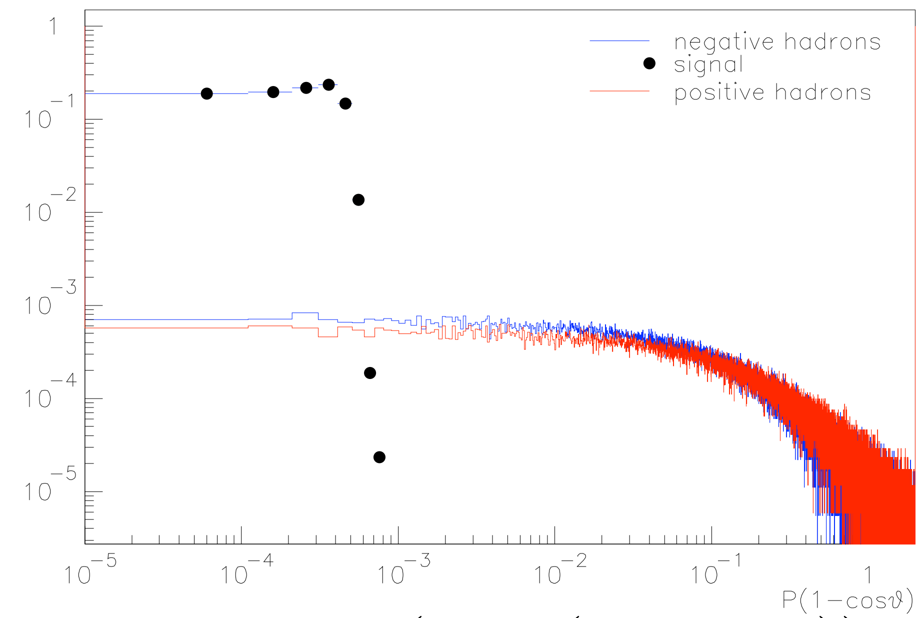
➾ ($\nu\mu$+$\nu\mu$-Bar+νe+νe-Bar)-Flux

Note: ≥91% is $\nu\mu$

Simulation of charged hadron background.



θ



$\zeta\ (\equiv P_e(1-\cos\theta))$

Background charge symmetric

Eff➢64%

Bkg➢ ≤10**(-6) ⇚ Measured

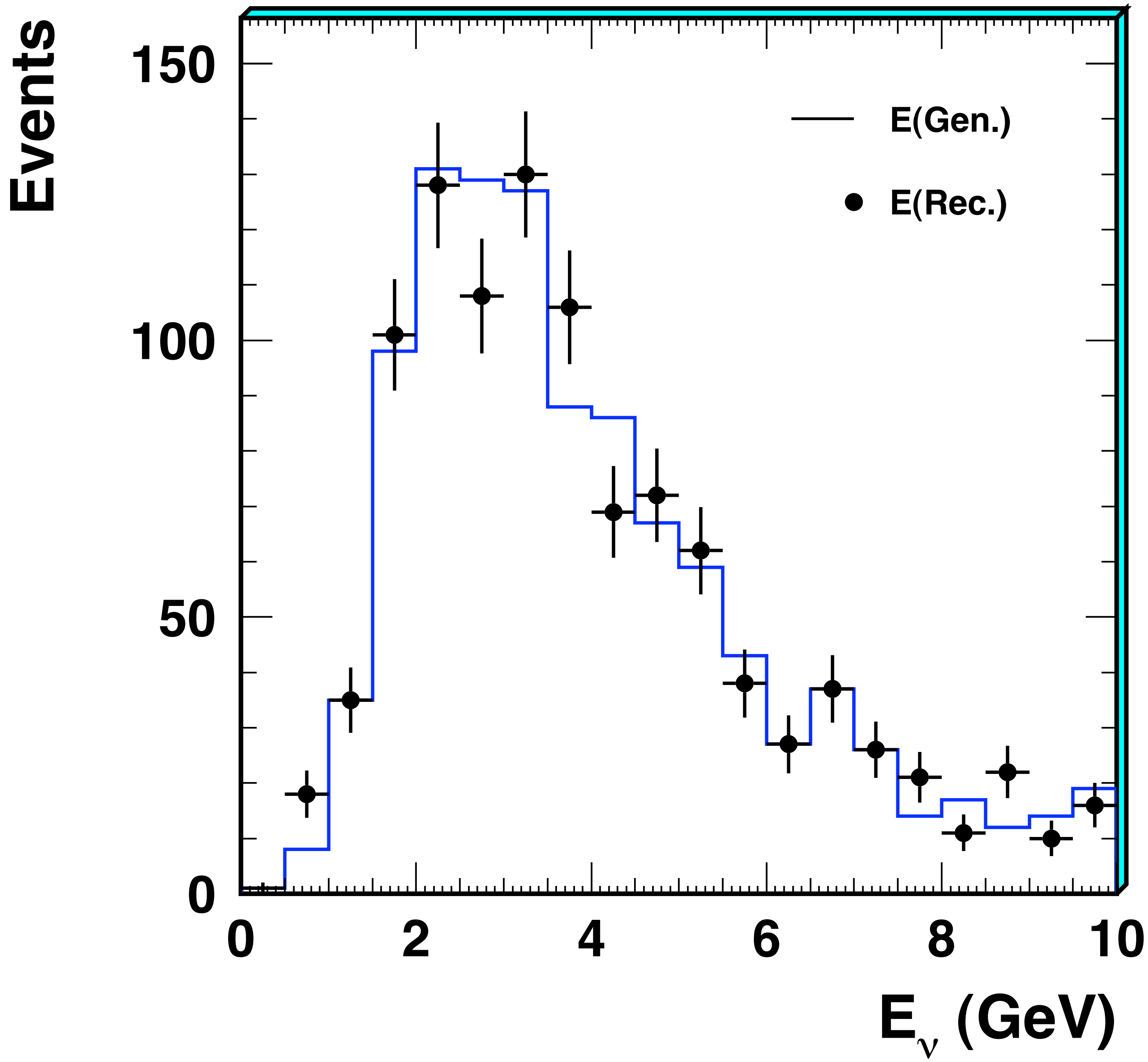
⇚ Conclusion

STT Signal 1,100 events, Background 6 events

STT: Yes   LAr: OK (High-Bkg)   Sci-Trk: No

ॐ Shape of Enu using (Ee, θe):

Statistically precision poorer than Low-ν0



LOW-ν_0 METHOD

- *Relative flux vs. energy from low-ν_0 method:*

$$N(E_\nu : E_{\rm HAD} < \nu^0) = C\Phi(E_\nu) f(\frac{\nu^0}{E_\nu})$$

the correction factor $f(\nu^0/E_\nu) \rightarrow 1$ *for* $\nu^0 \rightarrow 0.$

$\Longrightarrow$ *Need precise determination of the muon energy scale and good resolution at low* ν *values*

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docdb #300, #307

- *Fit Near Detector* $\nu_\mu, \bar{\nu}_\mu$ *spectra:*
  - *Trace secondaries through beam-elements, decay;*
  - *Predict* $\nu_\mu, \bar{\nu}_\mu$ *flux by folding experiental acceptance;*
  - *Compare predicted to measured spectra* $\Longrightarrow \chi^2$ *minimization:*

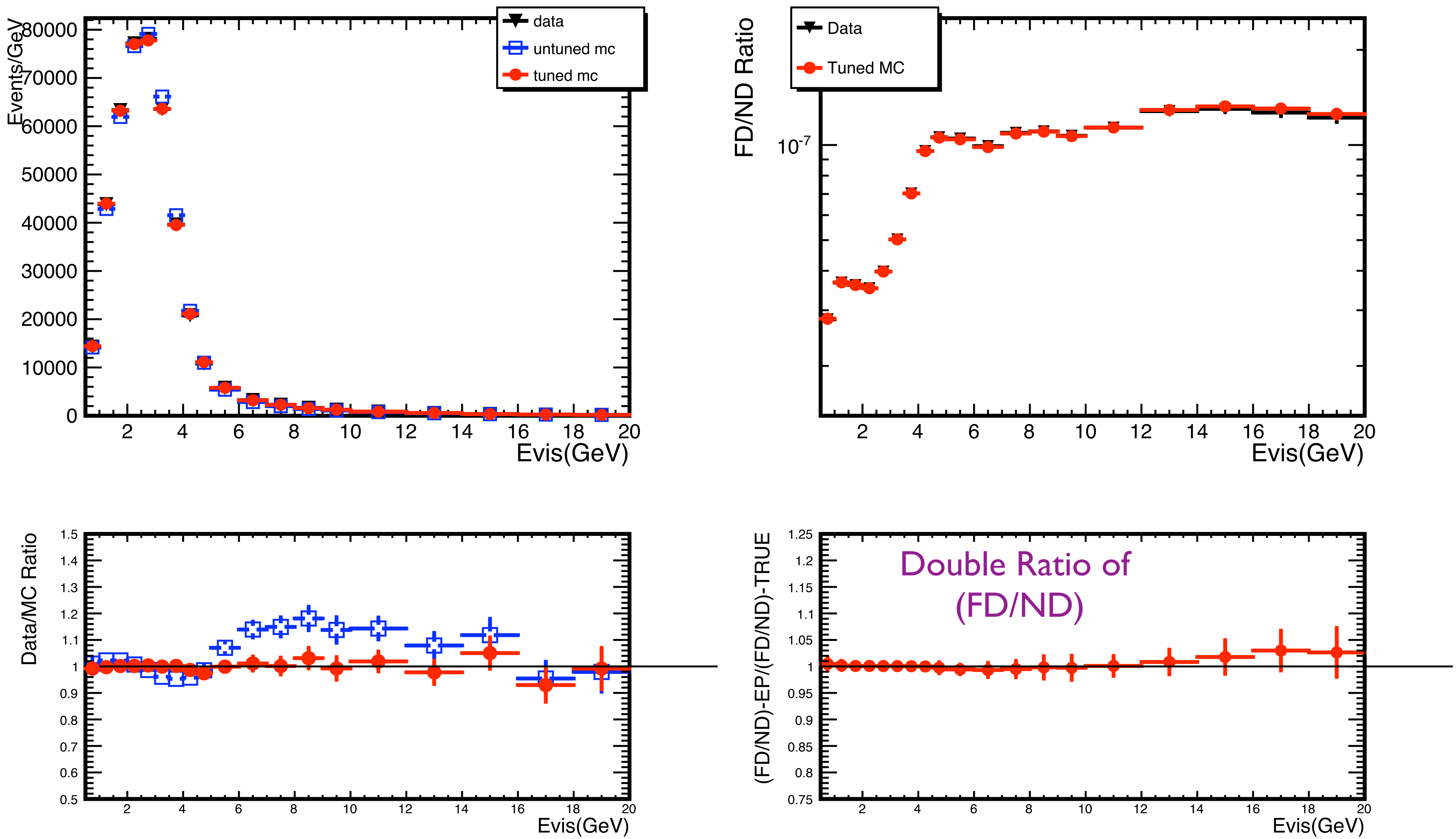
$$\frac{d^2\sigma}{dx_F dP_T^2} = f(x_F) g(P_T) h(x_F, P_T)$$

  - *Functional form constraint allows flux prediction close to* $E_\nu \sim \nu^0$.

STT: Ok,
LAr Ok with B,
Scint. Ok

- *Add measurements of* $\pi^\pm/K^\pm$ *ratios from hadro-production experiments to the empirical fit of the neutrino spectra in the Near Detector*

ν_μ, **Low-Nu0 Fit, ND at 500m** ⇚ Fit to $\nu\mu$-Data with Ehad<0.5 GeV [ν0]



Systematic-Errors in Low-ν0 Relative Flux: NuMu & Anti-NuMu

- Variation in ν0-cut
- Variation in ν0-correction
- Systematic shift in Ehad-scale
- Vary σ(QE) ±10%
- Vary σ(Res) ±10%
- Vary σ(DIS) ±10%
- Vary functional-forms
- Systematic shift in Emu-scale

- Beam-Transport (ND at 1000m)

Includes:

*Alignment (1.0mm)
*Horn Current (0.5%)
*Inert material (0.25λ)
*Proton spot size

⇒ Revisit these (?) & Investigate ND @ 500m

REDUNDANCY: ν_e & $\bar{\nu}_e$

✦ *Direct measurement of* $\boxed{\nu_e \text{ AND } \bar{\nu}_e}$ *spectra in the Near Detector provides a powerful cross-check of the flux predictions:*

$$\nu_e \equiv \mu^+(\pi^+ \rightarrow \nu_\mu) \oplus K^+(\rightarrow \nu_\mu) \oplus K_L^0$$

$$\bar{\nu}_e \equiv \mu^-(\pi^- \rightarrow \bar{\nu}_\mu) \oplus K^-(\rightarrow \bar{\nu}_\mu) \oplus K_L^0$$

✦ *In the NuMI beam* ν_e *and* $\bar{\nu}_e$ *independent flux predictions:*

$$\mu \Longrightarrow Well\ \ constrained$$

$$K^\pm \Longrightarrow Need\ \frac{K^+}{\pi^+} \& \frac{K^-}{\pi^-}\ \ MIPP$$

$$K_L^0 \Longrightarrow MIPP\ \ (NOMAD,\ \ HiResM\nu)$$

STT: Ok, LAr NO, Scint. NO

REQUIREMENTS FROM EXTERNAL MEASUREMENTS

- *We need the following external measurements from p-production experiments (e.g. MIPP at Fermilab):*
  - K^+/π^+ *as a function of* $P(2 \le P \le 20\ GeV)$ *&* $P_T(\le 0.4\ GeV)$ *of* K^+ *and* π^+
  - K^-/π^- *as a function of* $P(2 \le P \le 20\ GeV)$ *&* $P_T(\le 0.4\ GeV)$ *of* K^- *and* π^-
  - K^0/K^+ *ratio*
- *We need these measurements off:*
  - *LBNE neutrino target;*
  - *Thin/Thick Al, Cu, etc. targets that compose horn/beam-elements;*
  - *Air (N)*

DETECTOR REQUIREMENTS FOR OSCILLATION STUDIES

Flavor	Technique	Relative abundance	Absolute normalization	Relative flux $\Phi(E_\nu)$	Detector requirements
ν_μ	$\nu e^- \to \nu e^-$	1.00	3%	$\sim 5\%$	e identification/resolution e^-/e^+ separation
ν_μ	$\nu_\mu e^- \to \mu^- \nu_e$	1.00	3.5%		μ^-/μ^+ separation μ energy scale
ν_μ	$\nu_\mu n \to \mu^- p$ $Q^2 \to 0$	1.00	$3-5\%$	$3-5\%$	D target p angular and momentum resolution
ν_μ	low-ν_0	1.00		2.0%	Magnetized detector separating μ^-/μ^+
ν_e	low-ν_0	0.01	1-3%	2.0%	e^-/e^+ separation (K_L^0)

- In-situ measurement of flux normalization ~3%
- In-situ measurement of energy dependence ~2%
- Ratio ν_e/ν_μ to 0.1%

BACKGROUND MEASUREMENTS

- For the ν_e appearance search determine the π^0 yields as a function of E_{π^0} and θ_{π^0} in bins of hadronic energy $E_{\rm had}$:
  - Measure π^0 production in both NC and CC;
  - Correct MC background predictions predictions.

STT: Ok, LAr Ok, Scint. Ok

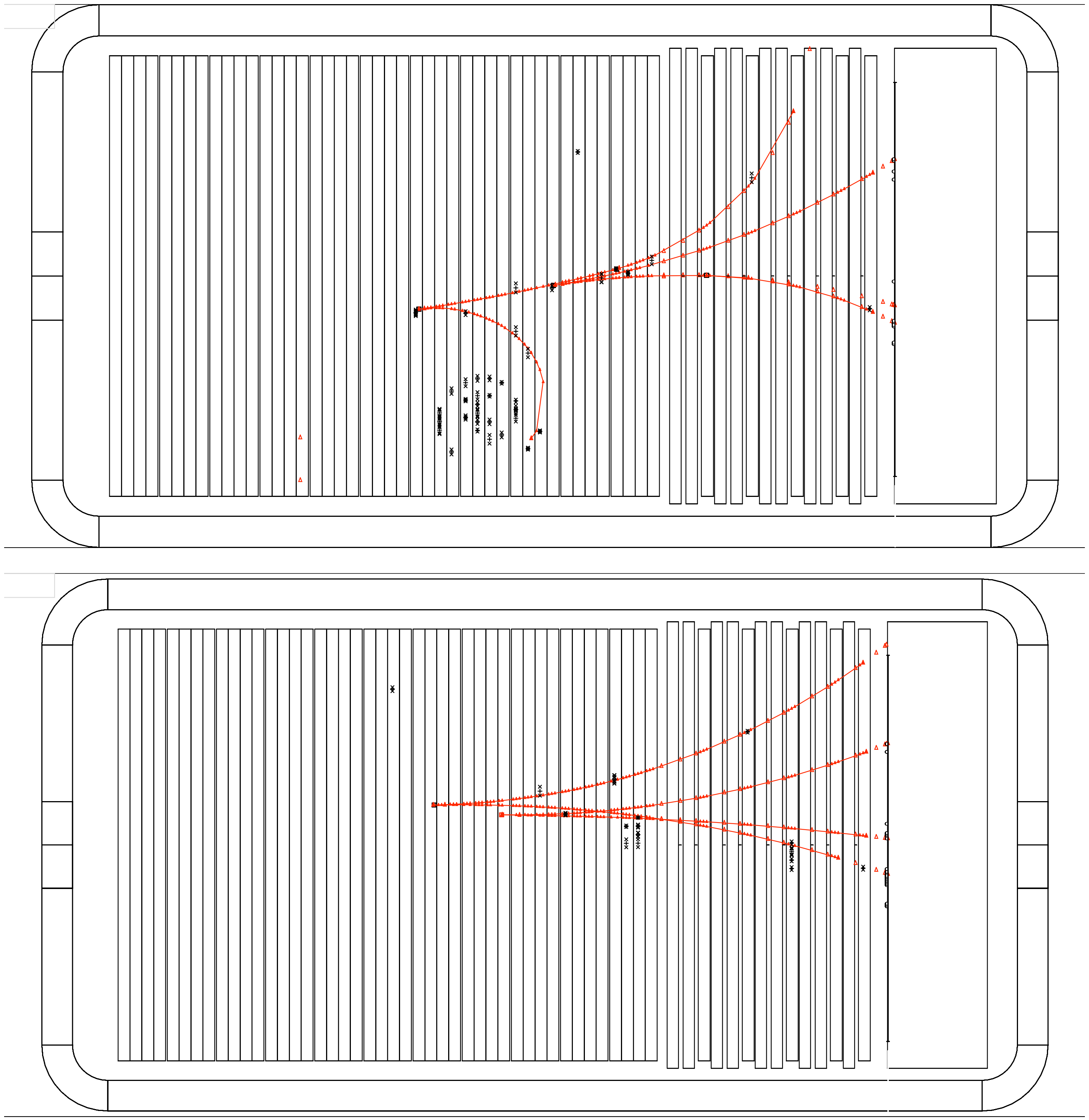
- For the $\nu_\mu(\bar{\nu}_\mu)$ disappearance search measure π^+ & π^- yields as a function of E_π and θ_π in bins of hadronic energy $E_{\rm had}$:
  - Measure π^0 production in both NC and CC;
  - Measure the rate of $\mu^\pm$ decays.

STT: Ok, LAr NO, Scint. NO

- Detailed study of cross section measurements in NOMAD and MINERvA

STT: Ok, LAr Ok, Scint. Ok

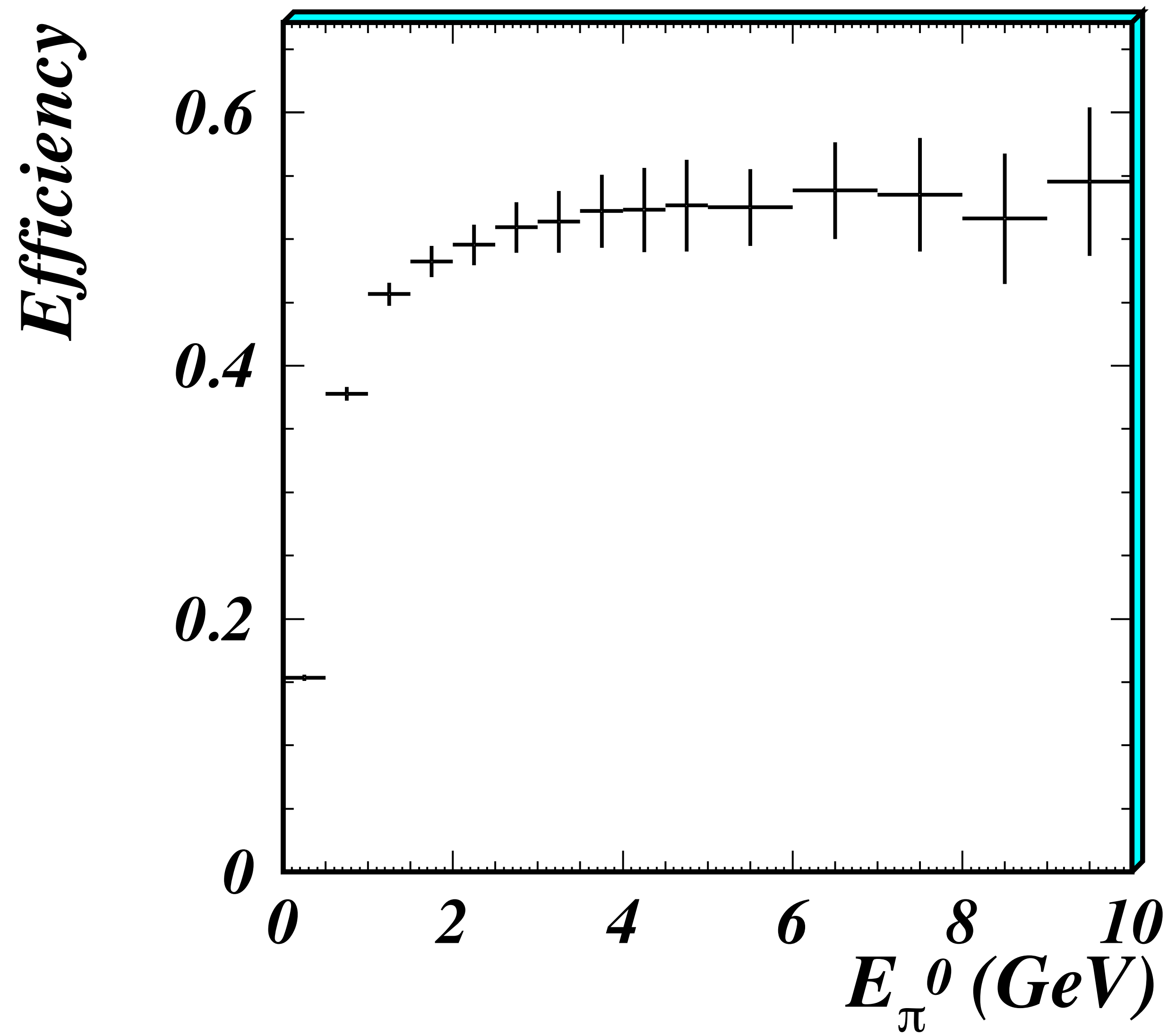
Coherent pi0 candidates in NOMAD



STT: Ok,
LAr Ok,
Scint. Ok

π0 Eff

STT: Ok,
LAr Ok,
Scint. Ok

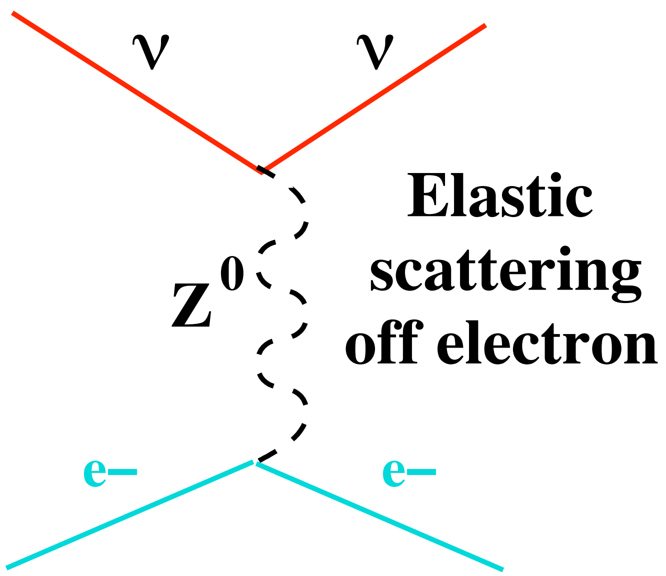


- ➢ At least one converted γ in STT
  (Reconstructed e- & e+;
  e- or e+ traverse ≥6 Mods)
- ➢ Another γ in the Downstream & Side ECAL

MEASUREMENT OF $\sin^2\theta_W$ FROM ν-e

✦ *Ratio of $\nu e \to \nu e$ and $\bar{\nu}e \to \bar{\nu}e$ NC elastic scattering, which is free from hadronic uncertainties:*

$$\boxed{R_{\nu e} \stackrel{\text{def}}{\equiv} \frac{\sigma(\bar{\nu}-e^-)}{\sigma(\nu-e^-)}}$$



✦ *Expected statistical uncertainty $\sim 1.0\%$. Systematic uncertainties related to the signal extraction reduced by $\nu/\bar{\nu}$ ratio and detector design:*

- *High resolution e tracking and charge measurement avoid background extrapolation (CHARM II);*
- *Electron energy measurement cancel in the ratio.*

- *Use the LAr detector present in the ND complex in front of the fine-grained tracker. The fiducial mass foreseen for the LAr is* ~ 100 *tons:*
  - *Total of* $\sim$ **80** $\times 10^3$ *NC events in* ν *mode;*
  - *Total of* $\sim$ **50** $\times 10^3$ *NC events in* $\bar{\nu}$ *mode.*

- *The optimal analysis uses a combination of* $\boxed{\text{TWO DETECTORS}}$*:*
  - *HiResMν provides a precise measurement of backgrounds (charge symmetric) and an overall calibration for LAr;*
  - *LAr provides the actual statistics for* $\sin^2\theta_W$ *and a good electron identification.*

- *Statistical uncertainty which can be reached on the ratio at the level of 0.3%*

- *Evaluated the uncertainty on the* $\bar{\nu}/\nu$ *flux ratio using the low-*ν_0 *method in the neutrino beam mode (positive focusing)*
  - *With current understanding of* $p/\pi/K$ *nuclear collisions and beam elements systematic uncertainty on theflux ratio of about 1%*
  - *Overall improvement on the* $\sin^2\theta_W$ *only a factor* ~ 1.4 *for a total uncertainty of* $\sim 0.56\%$

STT: Ok, LAr Ok high bkg, Scint. Ok?

MEASUREMENT OF Δs

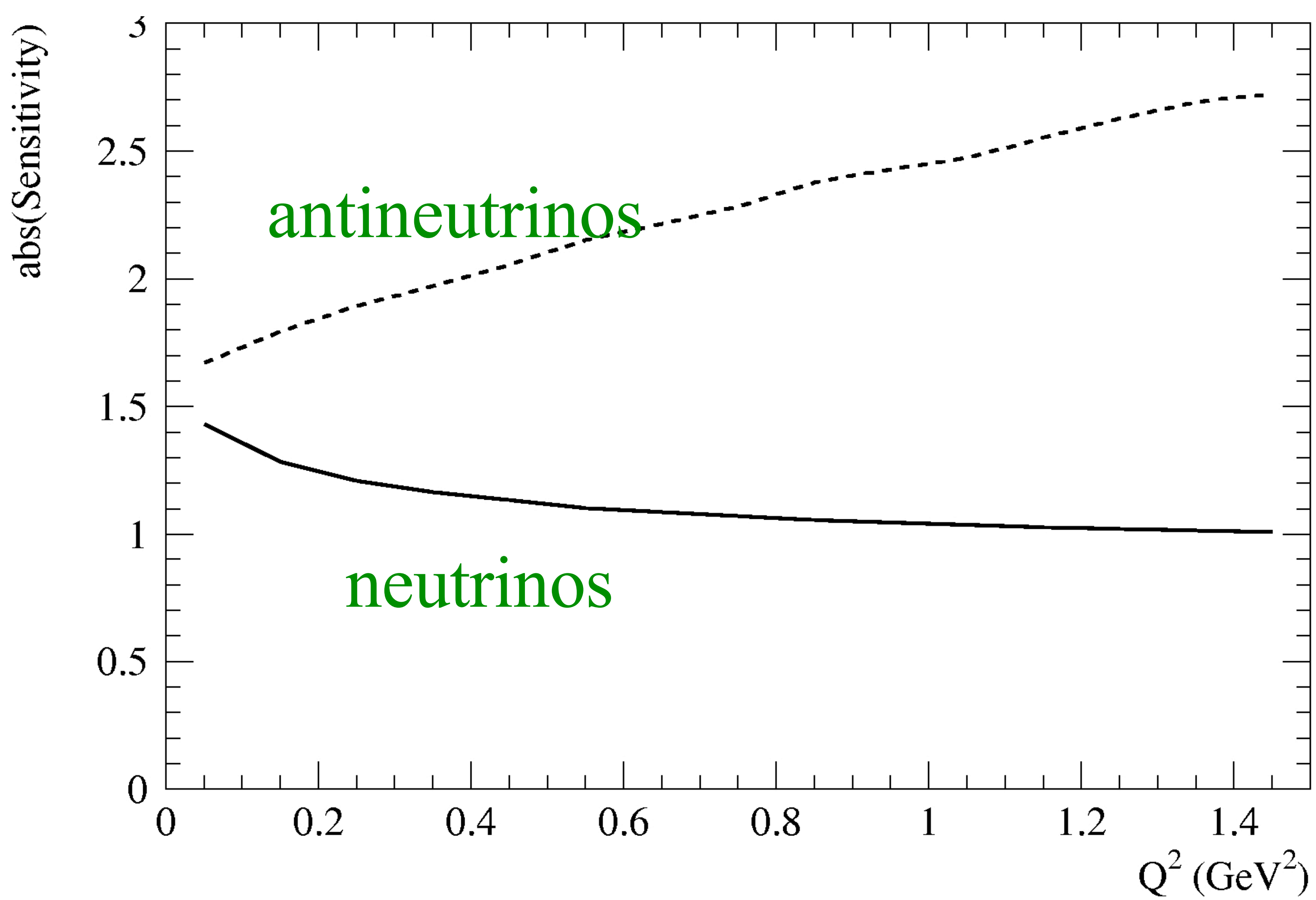
Gerry Garvey
and Rex Tayloe

$$R_\nu(NC/CC) = \frac{\sigma(\nu_\mu p \rightarrow \nu_\mu p)}{\sigma(\nu_\mu n \rightarrow \mu p)}$$

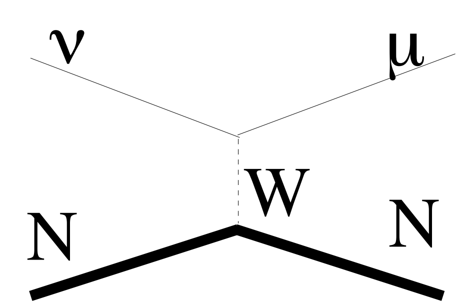
$$\overline{R}_\nu(NC/CC) = \frac{\sigma(\overline{\nu}_\mu p \rightarrow \overline{\nu}_\mu p)}{\sigma(\overline{\nu}_\mu p \rightarrow \mu n)}$$

$$\frac{d\sigma}{dQ^2}(\nu p \rightarrow \nu p) \propto (-G_A + G_A^s)^2$$

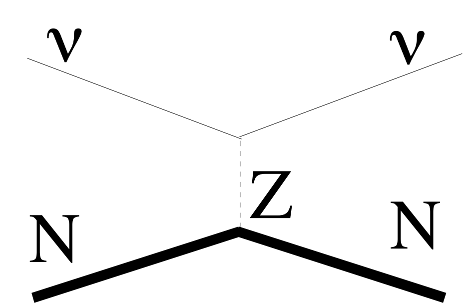
$G_A^s(Q^2 = 0) = \Delta s$



"CC": charged-current



"NC": neutral-current



*`Neutron' (Dirt) Bkg

MEASUREMENT OF THE RATIO $\mathcal{R}_{e\mu}$ ⇐ Impact of High-Δm**2 Oscillation

- *Independent analysis of neutrino data and anti-neutrino data due to possible differences following MiniBooNE/LSND results*

  $\Longrightarrow$ *Need a near detector which can identify e^+ from e^-*

- *Measure the ratio between the observed $\nu_e(\bar{\nu}_e)$ CC events and the observed $\nu_\mu(\bar{\nu}_\mu)$ CC events as a function of L/E_ν:*

$$
\begin{aligned}
\mathcal{R}_{e\mu}(L/E) &\equiv \frac{\#\ of\ \nu_e N \rightarrow e^- X}{\#\ of\ \nu_\mu N \rightarrow \mu^- X}(L/E) \\
\bar{\mathcal{R}}_{e\mu}(L/E) &\equiv \frac{\#\ of\ \bar{\nu}_e N \rightarrow e^+ X}{\#\ of\ \bar{\nu}_\mu N \rightarrow \mu^+ X}(L/E)
\end{aligned}
$$

- *Compare the measured ratios $\mathcal{R}_{e\mu}(L/E)$ and $\bar{\mathcal{R}}_{e\mu}(L/E)$ with the predictions from the low-ν_0 flux determination assuming no oscillations* ⇐ Need External K+/π+, K-/π0-, K0L/K+

- *Same analysis technique used in NOMAD to search for $\nu_\mu \rightarrow \nu_e$ oscillations.*

STT: Ok, LAr NO, Scint. NO

ainment of the events so reducing the usable statistics.

Measurement	STT	Sci+μDet	LAr	LArB	LArB+Sci+μDet	LAr+STT
In Situ Flux Measurements for LBL:						
$\nu e^- \to \nu e^-$	Yes	No	Yes	No	No	Yes
$\nu_\mu e^- \to \mu^- \nu_e$	Yes	Yes	No	Yes	Yes	Yes
$\nu_\mu n \to \mu^- p$ at $Q^2 = 0$	Yes	Yes	No	No	Yes	Yes
Low-ν_0 method	Yes	Yes	No	Yes	Yes	Yes
ν_e and $\bar{\nu}_e$ CC	Yes	No	No	Yes	Yes	Yes
Background Measurements for LBL:						
NC cross sections	Yes	Yes	No	Yes	Yes	Yes
π^0/γ in NC and CC	Yes	Yes	Yes	Yes	Yes	Yes
μ decays of $\pi^\pm, K^\pm$	Yes	No	No	Yes	Yes	Yes
(Semi)-Exclusive processes	Yes	Yes	Yes	Yes	Yes	Yes
Precision Measurements of Neutrino Interactions:						
$\sin^2\theta_W$ ν N DIS	Yes	No	No	No	No	Yes
$\sin^2\theta_W$ νe	Yes	No	Yes	No	No	Yes
Δs	Yes	Yes	Yes	Yes	Yes	Yes
νMSM neutral leptons	Yes	Yes	Yes	Yes	Yes	Yes
High Δm^2 oscillations	Yes	No	No	Yes	Yes	Yes
Adler sum rule	Yes	No	No	No	No	Yes
$D/(p+n)$	Yes	No	No	No	No	Yes
Nucleon structure	Yes	Yes	Yes	Yes	Yes	Yes
Nuclear effects	Yes	Yes	Yes	Yes	Yes	Yes

TABLE XXVIII: Summary of measurements that can be performed by different ND reference configurations.

Summary page from the Physics Report

Physics Outlook

ॐ Near Detectors provide systematic constraints, redundancy to discover/measure elements of PMNS matrix:

Discover something entirely new

ॐ New realm of precision measurements given the statistics (especially with proton-injector) and commensurate resolution

ॐ A rich program in ν-Precision measurements: Over 70 most sensitive measurements/searches